

## Green Transformation of Manufacturing for Environmental Protection in the Context of the Digital Economy

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**Abstract:** The development of the digital economy can significantly enhance resource utilization efficiency in the manufacturing industry and effectively monitor production emissions. This makes the digital economy a new driver for the green transformation of the manufacturing sector. As environmental protection becomes an increasingly pressing global concern, leveraging the digital economy to foster this transformation—by reducing energy consumption, water waste, and pollution emissions—has become a key issue that needs to be researched. To explore how to advance the green transformation of manufacturing and predict its future trajectory, this paper uses a system dynamics approach to simulate the process under various scenarios. The study demonstrates that accelerating the development of the digital economy has a considerable impact on improving resource utilization efficiency and reducing pollution emission, as does the improvement of green technology level. Notably, the improvement in green technology yields faster, more immediate environmental benefits, while the digital economy's impact is cumulative and becomes more pronounced over the long term. Therefore, it is essential to accelerate the digitization of the manufacturing industry and to improve green technology techniques and exploit their synergies. This paper aims to provide theoretical support and guidance for decision-making and practical actions within the manufacturing industry to enhance environmental protection.

**Keywords-** environmental protection, climate, sustainable water management, digital economy, green transition of manufacturing, system dynamics, sustainable development.

### 1. Introduction

The issue of environmental protection has long been a key global concern. In response to climate change and the degradation of the environment, the United Nations has consistently emphasized the importance of sustainable development in both the Rio Declaration on Environment and Development and Agenda 21. These frameworks highlight that sustainable development should be at the heart of long-term planning, aiming to "meet the needs of the present without compromising the ability of future generations to meet their own needs."

However, in practice, reconciling environmental protection with economic development is challenging, particularly in energy-intensive and high-emission industries such as traditional manufacturing. The growth of these industries has led to the rapid consumption of resources, increased pollution, and a host of other environmental problems. According to the laws of material conservation and energy, the outdated development model of traditional manufacturing exacerbates pressure on the Earth's environmental capacity. If this continues, economic growth will become unsustainable, and the difficulty of environmental restoration and governance will increase significantly. As such, it is imperative that countries adopt effective measures to promote the sustainable development of the manufacturing sector. The European Union has placed green transformation at the center of its economic development agenda, planning to invest 37% of its funds in green initiatives. The United States is similarly advancing clean energy and green manufacturing through the American Recovery Plan and the Infrastructure Investment and Jobs Act. Additionally, the UK, Norway, Canada, and other countries have introduced "green recovery plans" to support sustainable growth.

As a global manufacturing powerhouse, China plays a pivotal role in the world economy. In 2023, China's manufacturing sector contributed over 40 trillion yuan to its GDP, accounting for 26% of the total. For 13 consecutive years, it has ranked first in the world in terms of manufacturing output. However, this industrial growth comes with significant environmental costs. China's manufacturing industry accounts for one-third of the country's total carbon emissions and 29.2% of its water consumption. As the degradation of environment, China's reliance on an energy- and emissions-intensive development model is becoming increasingly unsustainable.

In response, the Chinese government has implemented a range of policies to promote sustainable manufacturing practices. These include the Guiding Opinions on Accelerating the Greening of the Manufacturing Industry and the 14th Five-Year Plan for Green Industrial Development, which outline clear goals for reducing energy and water consumption, pollution, and carbon emissions. The government has also called for curbing "two-high" (high energy consumption and high emissions) projects, optimizing industrial structures, and eliminating outdated production capacities. As environmental regulations tighten and the demographic dividend fades, the traditional model of "barbaric growth"—relying heavily on resource input and scale expansion—has proven unsustainable, inefficient growth has become an obstacle to economic development [1]. As a result, green transformation has become an unavoidable path for China's manufacturing sector.

In recent years, China has made great efforts in the green transformation of its manufacturing sector. In 2020, the energy intensity of manufacturing industry stood at 2.61 (10,000 tons of standard coal/trillion RMB), and carbon emission intensity was 1.05 (10,000 tons of carbon dioxide/trillion RMB). The reductions represent 15.7% and 21.5%, respectively, when compared to 2015. Water consumption per unit of industrial value-added was 14.31 m<sup>3</sup>/million yuan, a 42.2% decrease from 2015. Additionally, chemical oxygen demand (COD) emissions fell to 395,266 tons, a drop of 82.95% from 2015. These improvements demonstrate that China's manufacturing sector is beginning to reap the benefits of its green transformation efforts. China has made some breakthroughs in the green transformation of its manufacturing sector.

In the process, the rapid growth of the digital economy is providing fresh momentum for the green and low-carbon transformation of the manufacturing industry [2]. Between 2014 and 2023, China's digital economy grew from 16.1 trillion RMB to 55 trillion RMB, reflecting an average annual growth rate of 16%. This growth notably outpaced the country's GDP expansion during the same period. With its extensive reach, the digital economy can be deeply integrated into the manufacturing sector to enhance production efficiency while simultaneously reducing resource consumption. According to the Development Report on Digital Greening and Collaborative Transformation (2024), digital technologies are increasingly showcasing their systemic, synergistic, and holistic potential. These technologies are expected to extend their influence on the green transformation of the manufacturing industry from isolated processes to multiple interconnected links within the value-chain. The future of manufacturing is anticipated to align with the trend of "Digitalization and Green Convergence"[3], which focuses on utilizing technologies like 5G and big data to digitize every aspect of the manufacturing process, including management and production. The ultimate aim is to establish a sustainable manufacturing while advancing the dual transformation of digital and green practices across the sector [4].

Under the background of digital economy, how to realize further development of manufacturing industry in terms of reducing resource consumption and emissions, and what effective measures can be taken to promote green transformation are still key issues that need to be solved urgently. To address these issues, this paper takes into account the development trend of "digital-green integration" and adopts the system dynamics (SD) approach. This paper presents a system dynamics (SD) model that views the manufacturing production and digital economy as an interconnected system. This model forecasts changes in key indicators, such as energy consumption, water consumption, carbon emissions, and wastewater discharge. Furthermore, the paper explores various measures that could accelerate the green transformation by setting up different scenarios. It proposes an optimal path for the green transformation manufacturing, offering valuable insights and a basis for the sustainable development strategy of the manufacturing sector in the digital economy era.

## 2. Literature Review

### 2.1 Research on Green Transition of Manufacturing

The green transformation of manufacturing involves an escalation from the traditional development model, which is often associated with massive resource consumption and pollution, to a more sustainable development that emphasizes eco-friendly [5]. This transition is characterized by five key attributes: advanced technology, excellent economic benefits, reduced resource consumption, eco-friendly, and the optimal utilization of human resources [6].

Previous research on the green transformation of manufacturing has mainly concentrated on identifying the factors that drive this shift, such as innovation and environmental regulation. These studies typically utilize econometric methods to analyze the impact of these factors on the transition under different conditions. Among these, innovation stands out as a crucial element, as technological advancements can significantly contribute to reducing carbon emissions and enhancing the efficiency of water usage [7,8]. Furthermore, technological innovation exhibits a spillover effect, where an increase in local R&D intensity can enhance the capacity to absorb technological innovation from vicinity [9]. Process innovation can work in tandem with environmental regulation practices to further enhance both energy and water efficiency [10]. Environmental regulations can motivate manufacturing enterprises to undertake a green transformation, helping them achieve greater economic benefits while simultaneously reducing carbon emissions [11,12]. Effective environmental regulations can stimulate innovation in the industry, fostering the simultaneous advancement of both environmental protection and economic benefits [13]. However, in short-term development, strict environmental regulations may impede the improvement of competitiveness in manufacturing [14]. Productive services can complement manufacturing to enhance green total factor productivity [15,16], with higher-end productive services having a greater impact [17]. Other factors, including the upgrading of industrial structure [18] and the optimization of energy structure [19], also play an important role in reducing carbon emissions in manufacturing. Although market competition can improve the green production efficiency of manufacturing, it may also deter investment in research and development [20].

In recent years, as the influence of the digital economy has gradually expanded, attention has shifted toward understanding how the digital economy affects the green transition of manufacturing and its possible development trends.

### 2.2 The Impact of the Digital Economy on the Green Transformation of Manufacturing

The digital economy can influence the green transformation of manufacturing in two key ways: digital industrialization and industrial digitization. Digital industrialization refers to the development of data elements and digitization techniques. In contrast, industrial digitization involves the digital transformation of traditional industries. In these ways, the digital economy will shape the green transformation of the manufacturing industry, influencing production processes, marketing, and the development environment.

#### 2.2.1 The impact of the digital economy on the production process

In the production process manufacturing, the digital economy promotes the green transformation of manufacturing mainly through the following ways

Firstly, the digital economy enhances the level of collaboration in the production processes of manufacturing enterprises through its integration capabilities. By leveraging digital technologies, the manufacturing industry can achieve integration throughout the entire industrial value chain [21], to enhance resource efficiency and achieve green production [22,23]. In terms of technological research, the digital economy can increase technological spillovers by lowering the interaction costs between sectors [24]. New green technologies can also be more widely adopted, enabling manufacturing companies to optimize their production processes, reduce resource consumption and pollutant emissions [25-27].

Second, digital industrialization can also drive the sustainable development of the manufacturing industry [28]. Manufacturing enterprises can leverage big data to foster green demand [29]. Digital twin can optimize production solutions [30], help manufacturing enterprises increase their revenue while reducing the costs of green transformation [31].

### ***2.2.2 The impact of the digital economy on the market***

The digital economy can support the green transformation of the manufacturing sector on the market side by developing e-commerce platforms and promoting the circular economy. [32-34]. For example, sensor combined with the Internet of Things (IoT), can enable precise detection of emissions and facilitate waste recycling[35].The development of e-commerce can also support this process [36]. Through the e-commerce model, companies can achieve resource savings by adopting flexible production methods [37,38].

### ***2.2.3 The impact of the digital economy on the development environment***

The digital economy will alter the development environment of the manufacturing industry, making companies more likely to embrace a green transition. The main reason for this phenomenon is the synergistic effects of the digital economy and environmental regulations on governance [39]. The government can enhance communication with communities in polluted areas through digital governance and use information technology to accurately monitor corporate emissions [40-42]. In addition, improving digital infrastructure can help enterprises address financing challenges and enhance the efficiency of resource utilization in production, thereby supporting their sustainable development [43-47].

## **2.3 Research on Green Transition Forecasting**

Existing studies on forecasting the green transformation of the manufacturing industry typically focus on predicting development trends and comparing the manifestations of various scenarios. These studies often involve constructing models that account for the key variables influencing carbon emissions. For example, Chaofan Chen uses the directional distance function and the Malmquist-Luenberger productivity index to predict the economic efficiency and green productivity of the manufacturing industry under different policy combinations, aiming to identify the optimal path for energy savings and emission reductions [48]. Similarly, Chaojun Yang integrates the impacts of technology, market factors, and environmental regulations on the manufacturing industry, using a system dynamics model to analyze the dynamic effects of these variables on the green development of the sector [49]. In addition to these approaches, machine learning and computable general equilibrium (CGE) models are frequently employed to simulate the development of the manufacturing industry under various scenarios [50-52].

## **2.4 Limitations of Existing Research**

While existing research offers valuable insights, it also has significant limitations. First, existing studies often focus on a single variable or process when examining the role of the digital economy in the green transition. However, the impact of the digital economy on the manufacturing industry is far more comprehensive, and its effects unfold within a complex system. Current research on the dynamics of this complex system remains insufficient. Second, when modeling the development of the manufacturing sector, existing studies often overlook the digital economy as a contextual factor and fail to consider it as a key influence.

## **2.5 Research Objectives and Innovations**

This paper aims to fill existing gaps by constructing a system dynamics model for the green transformation of manufacturing. This model will reveal the relationship between different variables within the system of green transformation of manufacturing under the influence of the digital economy. In addition, the model will make predictions about the growth of the manufacturing sector, including value-added, water consumption, energy use, carbon emissions, and pollution emissions.

This approach expands on the limited scope of previous studies, emphasizing the complexity of the digital economy's role in green transformation process of manufacturing

### **3. Methods: System Dynamics Modeling**

System Dynamics Theory, developed in the 1960s by MIT professor Jay Forrester as part of Industrial Dynamics, was initially used to study the production, operations, and management of American industrial firms. Today, the System Dynamics approach is widely applied in fields such as economics, society, and politics.

#### **3.1 System Boundary**

The object of this paper is the green transformation of the manufacturing industry and the model period is from 2014 to 2035. Based on existing research, we divide the system into five subsystems.

##### ***3.1.1 Socio-economic subsystem***

The socio-economic subsystem forms the foundation of manufacturing operations, which includes key variables such as GDP and demographic.

The growth of GDP will expand the production scale of manufacturing enterprises through investment, while population provides the workforce for these enterprises. The digital economy within this system will impact the R&D, production, and emissions processes of manufacturing industries, making it a key variable.

##### ***3.1.2 Manufacturing production subsystem***

The manufacturing production subsystem represents the production process of the manufacturing sector, within which manufacturing is divided into high-carbon industries and low-carbon industries. High-carbon industries include non-metallic mineral products, ferrous metal smelting and rolling industries, non-ferrous metal smelting and rolling industries, chemical raw materials and chemical products manufacturing, as well as petroleum processing, coking, and nuclear fuel processing industries, the remaining industries are classified as low-carbon industries. Changes in the proportion of high-carbon and low-carbon industries within manufacturing will affect overall economic returns, resource consumption, and emissions.

##### ***3.1.3 R&D subsystem***

The R&D subsystem represents a series of research and development activities within the manufacturing sector. Increased investment in R&D will lead to more technological innovations, which will enhance the economic efficiency of manufacturing, but it may also increase energy consumption, becoming a burden for enterprises. The proportion of green patents reflects the level of focus that manufacturing industries place on green technologies. The proportion of green patents represents the level of attention manufacturing industries give to green technologies.

##### ***3.1.4 Energy and carbon emission subsystem***

The energy and carbon emission subsystem represents the energy consumption and the resulting carbon emissions during the production process. In this process, production and innovation in manufacturing typically mean an expansion of capacity, which leads to an increase in energy consumption. The digital economy and the level of green technology can optimize manufacturing production, thus exerting a suppressive effect on energy consumption. Energy consumption leads to corresponding carbon emissions. The carbon emissions of manufacturing are influenced by the carbon emission factor of energy and the level of electrification.

##### ***3.1.5 Water consumption and sewerage subsystem***

In the water consumption and sewerage subsystem, water usage is determined by factors such as the value added by the manufacturing industry, the size of the digital economy, and the number of green patents. A rise in manufacturing value added typically leads to expanded production capacity, which in turn increases water



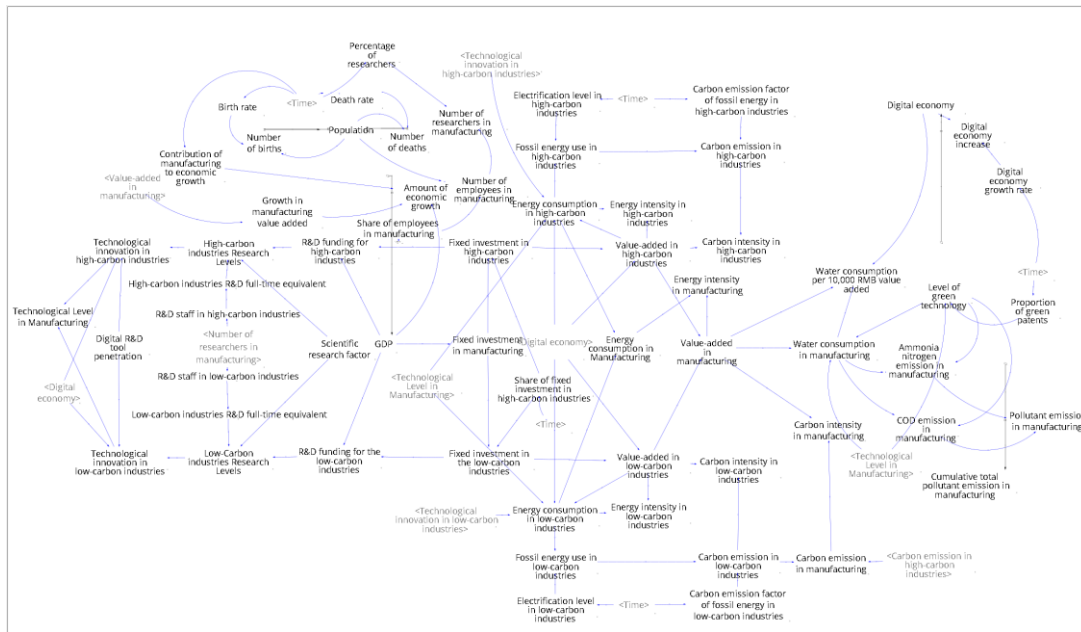


Figure 2. The flow diagram for green transition of manufacturing

Table 1. Model major equations

<b>State Variables:</b>
Population=INTEG (Number of births - (Number of deaths,136726)
GDP=INTEG (Amount of economic growth,643563)
Digital economy=INTEG (Amount of Digital economy growth,16100)
Cumulative total pollutant emission in manufacturing=INTEG (Pollutant emission in manufacturing, 0)
<b>Rate Variables:</b>
Amount of economic growth=Growth in manufacturing value added/Contribution of manufacturing to economic growth
Amount of Digital economy growth=Digital economy growth rate*Digital economy
Pollutant emission in manufacturing=Ammonia nitrogen emission in manufacturing +COD emission in manufacturing
<b>Auxiliary Variables:</b>
Energy consumption in High-Carbon industries = EXP (2.759) *Value added in high-carbon industries <sup>(1.118)</sup> *Digital economy <sup>(-0.526)</sup> *Level of green technology <sup>(-0.161)</sup> *Technological innovation in high-carbon industries <sup>(0.466)</sup>
Energy consumption in low -carbon industries =EXP (-4.582) *Digital economy <sup>(-0.785)</sup> * Technological innovation in low-carbon industries <sup>(0.781)</sup> *Level of green technology <sup>(-0.435)</sup> *Value added in low-carbon industries <sup>(1.653)</sup>
Value added in low-carbon industries =Low-carbon industries value added = EXP (3.195) *Fixed investment in low-carbon industries <sup>0.404</sup> *Technological innovation in low-carbon industries <sup>0.184</sup> *Digital economy <sup>0.119</sup>
Water consumption in manufacturing=EXP (6.22) *Value added in manufacturing <sup>(0.31)</sup> *Digital economy <sup>(-0.218)</sup> *Level of green technology <sup>(-0.293)</sup> *Technological Level in Manufacturing <sup>(0.158)</sup>
COD emission in manufacturing=EXP (-5.55) *Water consumption in manufacturing <sup>(4.552)</sup> *Level of green technology <sup>(-0.751)</sup>
Ammonia nitrogen emission in manufacturing=EXP (4.827) *Water consumption in manufacturing <sup>(3.285)</sup> *Level of green technology <sup>(-0.976)</sup>

### 3.3 Model Validity Test

After simulating using Vensim software, this study obtained the simulation values of various variables. In order to validate the model's effectiveness, the study compared the simulation values of key variables in the system with historical values. The historical values are derived from actual data from 2014 to 2021.

The error between the simulation values and the historical values will be calculated as follows.

$$\varepsilon = (y^s - y^t)/y^t \quad (1)$$

Where  $y^s$  and  $y^t$  denote the simulated value and actual values of the system at moment  $t$ , respectively. Table 2 reflects the results of the historicity test of the main variables in the system.

Table 2. Historical test results

Time (Year)	Water consumption in manufacturing			Value added in manufacturing		
	Simulated value	Historical value	Relative error	Simulated value	Historical value	Relative error
2014	517.758	501.92	3.16%	189620.60	195620.30	-3.07%
2015	501.131	494.04	1.44%	201348.70	199436.00	0.96%
2016	483.177	484.12	-0.19%	217163.60	209508.90	3.65%
2017	455.022	472.65	-3.73%	233687.90	233876.46	-0.08%
2018	438.203	466.95	-6.16%	249249.50	255937.16	-2.61%
2019	420.81	450.66	-6.62%	260928.90	264136.72	-1.21%
2020	404.442	381.37	6.05%	276888.10	266417.77	3.93%
2021	404.637	388.48	4.16%	295783.70	291993.87	1.30%
Average error	Water consumption in manufacturing		3.94%	Value added in manufacturing		2.10%
	Energy consumption in Manufacturing			Carbon emission in manufacturing		
Time (Year)	Simulated value	Historical value	Relative error	Simulated value	Historical value	Relative error
2014	246043.60	248976.00	-1.18%	729616.00	738718.32	-1.23%
2015	249232.70	248264.00	0.39%	748819.00	746054.01	0.37%
2016	253406.80	247658.00	2.32%	756027.00	738616.07	2.36%
2017	254585.90	252462.00	0.84%	724405.00	718297.28	0.85%
2018	258333.10	258604.00	-0.10%	747899.00	750440.69	-0.34%
2019	266814.20	268426.00	-0.60%	789766.00	795347.58	-0.70%
2020	280084.20	279651.00	0.15%	828712.00	827861.45	0.10%
2021	304435.50	293065.00	3.88%	876462.00	843092.66	3.96%
Average error	Energy consumption in Manufacturing		1.18%	Carbon emission in manufacturing		1.24%

As we can see, the maximum error between the simulation values and historical values in Table 3 is 6.62%, with the error between simulation and historical values remaining within 5% in most years. Additionally, the average error for each index is no more than 5%. These results indicate that the system has high precision, good fit, and is capable of reliable simulation and prediction.

#### 4. Results and Discussion

To explore the dynamic impact of various factors on the green transition of manufacturing and its potential future development, this paper analyzes three key input variables: digital economy growth rate, scientific research factor, and the proportion of green patents. Seven distinct scenarios are designed by adjusting the values of these variables, with the specific scenarios outlined in Table 3. The study examines the development of China's manufacturing industry under these different scenarios. The current scenario represents the manufacturing's development assuming that all variables remain constant at their current levels. In contrast, the other scenarios reflect development outcomes for the manufacturing, with adjustments made for specific variables. Key variables evaluated in the scenario simulations include: value-added in manufacturing, pollutant emission in manufacturing, water consumption in manufacturing, energy demand in manufacturing and carbon emission in manufacturing.

Table 3. Variable settings in each scenarios

Scenario	Measure	Digital economy growth rate	Scientific research factor	Proportion of green patents
Current	Keeping the current scenario unchanged	10%	1	12%
C1	Increase digital economy growth rate	12%	1	12%
C2	Decrease digital economy growth rate	8%	1	12%
C3	Increase research Levels of <b>manufacturing</b>	10%	1.05	12%
C4	Decrease research Levels of <b>manufacturing</b>	10%	0.95	12%
C5	Increase Level of green technology	10%	1	14%
C6	Decrease Level of green technology	10%	1	10%

Simulation of the seven scenarios is carried out through Vensim software to observe the operation of the system model under different scenarios modes, the simulation time is set as 2014-2035, and the simulation step is 1 year, focusing on the comparison between different scenarios and Scenario Current.

##### 4.1 Comparison of Value-added in Manufacturing

After simulating different scenarios using Vensim software, we can compare the value added in manufacturing under various scenarios, as shown in Figure 3.

In terms of value added in manufacturing, accelerating the development of the digital economy and increasing research levels can positively impact the growth of value-added manufacturing. In Scenario C1 and Scenario C3, the value added in manufacturing industry in 2030 increases by 4.56% and 0.67%, respectively, compared to the Current scenario.

The digital economy has a more significant effect on the economic efficiency of the manufacturing industry. By improving the digitization of manufacturing, the digital economy reduces communication and interaction costs, allowing the manufacturing sector to better leverage the innovation outcomes of other industries. Regarding research levels, increasing research levels up to a certain threshold can enhance product innovation, thereby boosting the value added of manufacturing enterprises. However, beyond this threshold, further R&D investment leads to diminishing returns and may even waste resources [53]. In Chinese mature manufacturing sector, many enterprises are approaching this threshold, meaning that excessive R&D investment in the traditional form may lead to inefficiency.

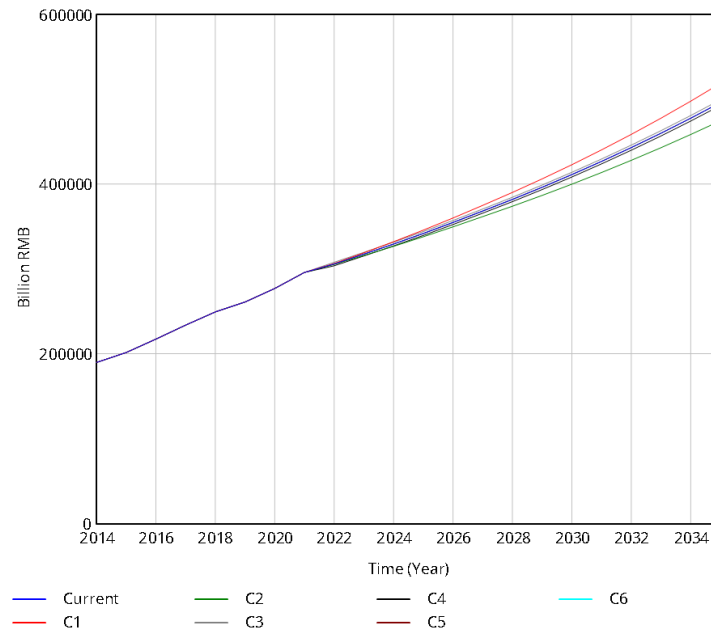


Figure 3. Value added in manufacturing under different scenarios

#### 4.2 Comparison of Energy and Carbon Emission in Manufacturing

Simulations using Vensim software provide insights into energy demand and carbon emission across different scenarios, as illustrated in the Figure 4-7 below.

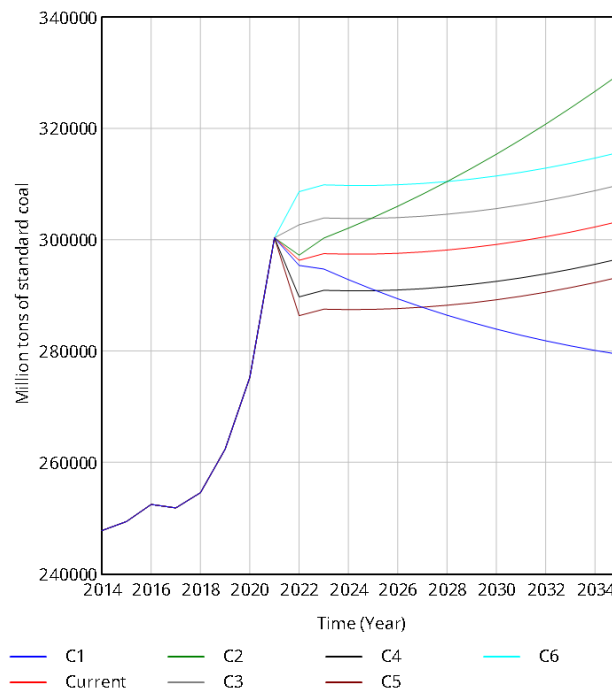


Figure 4. Energy consumption in manufacturing under different scenarios

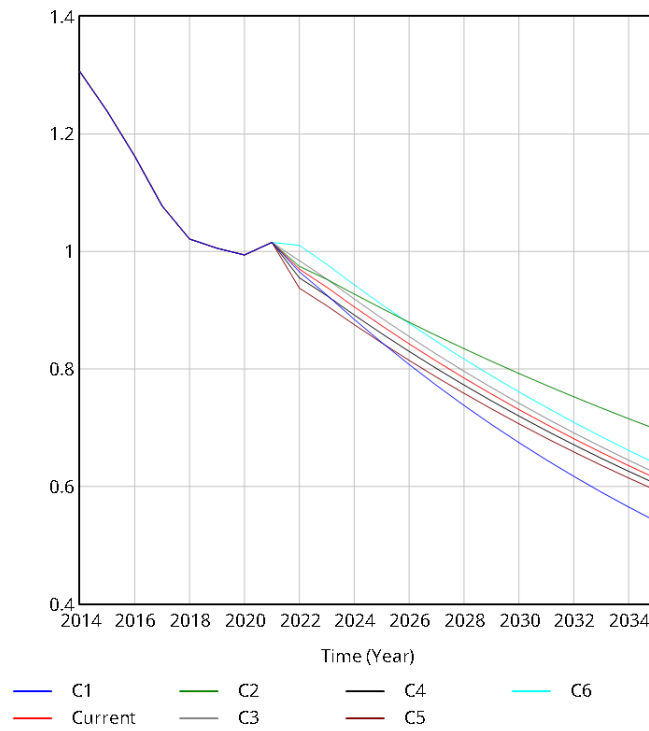


Figure 5. Energy intensity under in manufacturing different scenarios

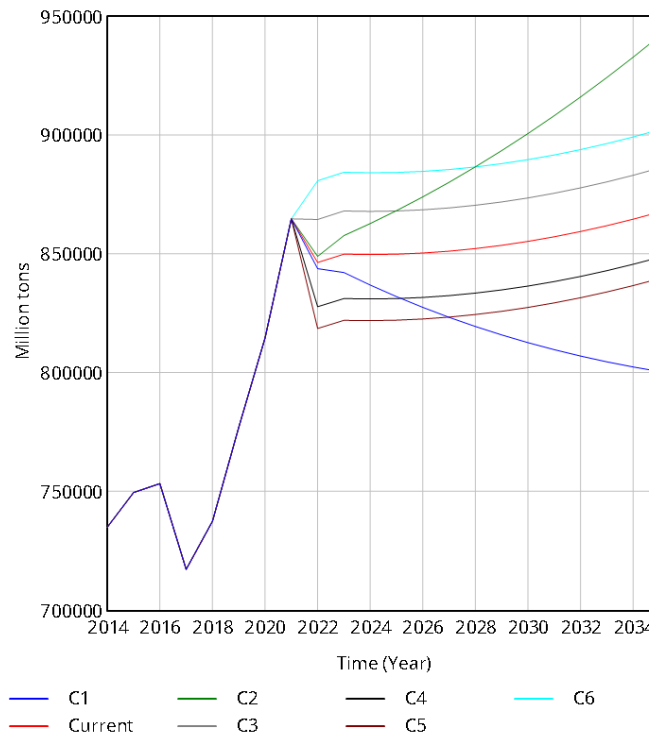


Figure 6. Carbon emission in manufacturing under different scenarios

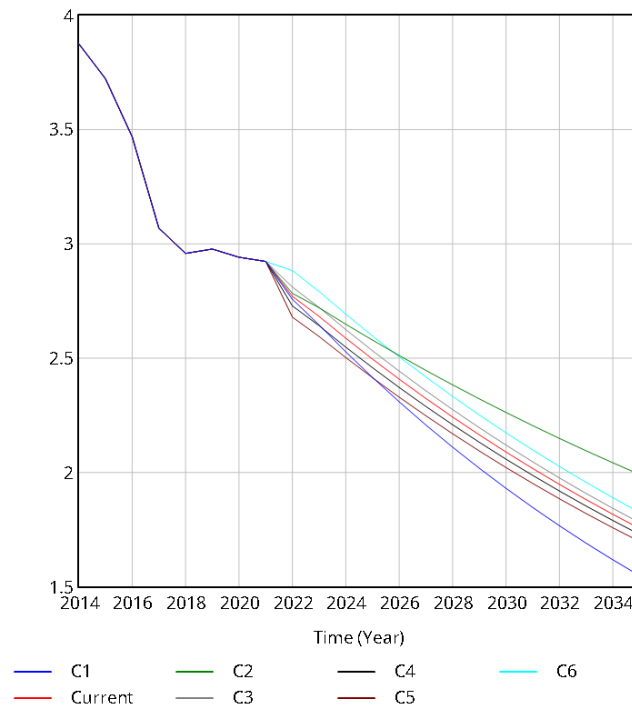


Figure 7. Carbon intensity in manufacturing under scenario under different scenarios

By analyzing energy and carbon emission indicators in various scenarios, it becomes clear that accelerating digital economy development, reducing scientific research factor, and increasing the proportion of green patents can help reduce both energy consumption and carbon emissions in the manufacturing industry.

In Scenario C1, accelerating the digital economy improves energy efficiency and reduces both energy intensity and carbon intensity. The enhanced economic efficiency driven by digitalization supports these reductions. In Scenario C4, manufacturing can reduce energy and carbon intensity by cutting energy use, though this may come with some loss of economic benefits. Meanwhile, Scenario C6, which increases the level of green technologies, allows manufacturing enterprises to adopt more efficient, eco-friendly production methods. This reduces both energy consumption and carbon emissions while maintaining economic efficiency.

When comparing the development of indicators across time periods, adjustments in Scenario C4 and Scenario C6 help quickly bring energy demand and carbon emissions under control. However, the impacts in Scenario C1 are slower to materialize. The reason is that the impact of the digital economy has a cumulative effect.

#### 4.3 Comparison of Water Consumption in Manufacturing

Simulations using Vensim software also allow for a comparison of water consumption and water use efficiency in the manufacturing industry under different scenarios, as shown in Figure 8-9.

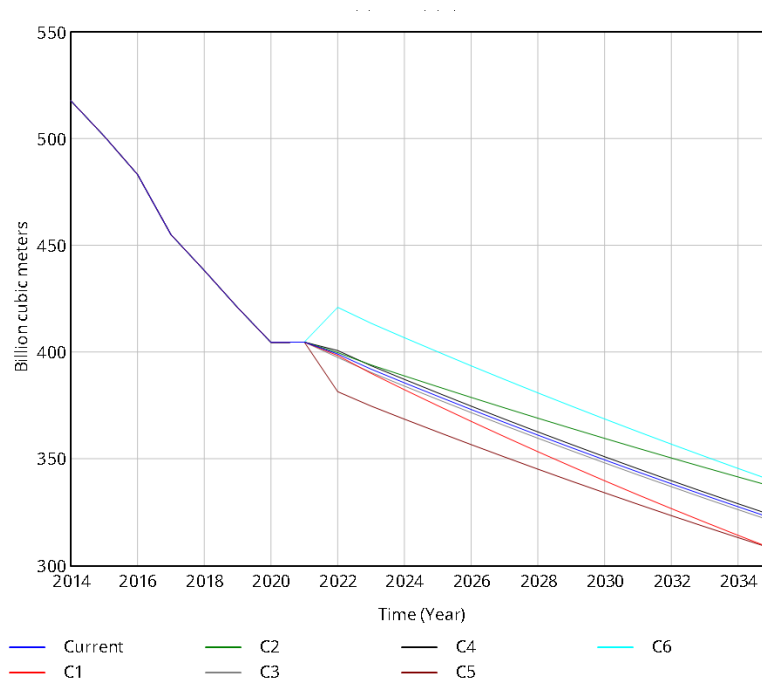


Figure 8. Water consumption in manufacturing under different scenarios

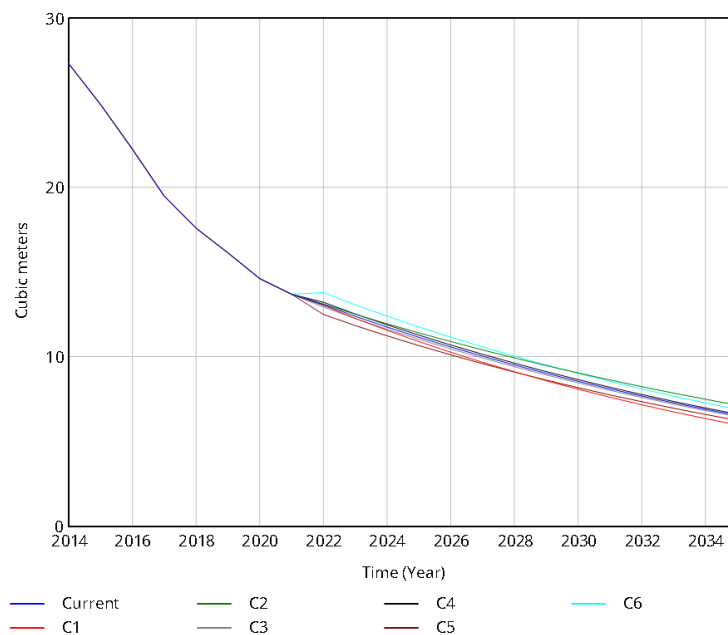


Figure 9. Water consumption per 10,000 RMB value added under different scenarios

Manufacturing enterprises can reduce water consumption by accelerating the digital economy and increasing the proportion of green patents. The water-saving effect of green patents adoption is more immediate, while the benefits of the digital economy are slower to emerge.

In Scenario C1 and Scenario C5, which represent an increase digital economy and a higher share of green patents in manufacturing, water consumption in both scenarios will be equal by 2035. Compared to the Current Scenario, water consumption in both scenarios decreases by 4.4%, reflecting a more sustainable status quo.

In terms of water use efficiency (measured as "water use per 10,000 Yuan of value added"), Scenario C1 performs the best among all scenarios. The digital economy's boost to economic efficiency in the manufacturing sector leads to significant improvements in this indicator.

When comparing Scenario C3 and Scenario C4, we find that adjusting research levels in the manufacturing sector alone has a smaller impact on water consumption. In Scenario C3, increasing R&D inputs raises both water use and value added, improving water use efficiency. In contrast, Scenario C4 sees a decrease in water use efficiency compared to the Current Scenario.

#### 4.4 Comparison of Pollutant Emission in Manufacturing

After simulation by Vensim software, we can get the comparison results of pollutant emission and cumulative pollutant emission in manufacturing under different scenarios, as shown in Figure 10-11.

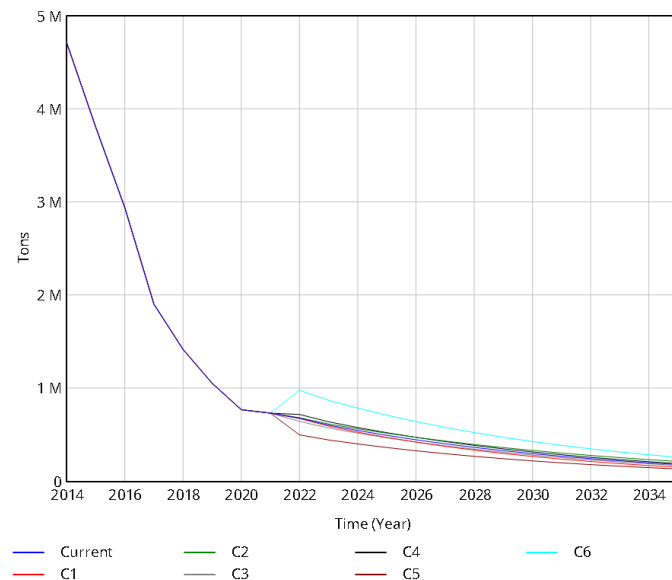


Figure 10 Pollutant emissions in manufacturing under different scenarios

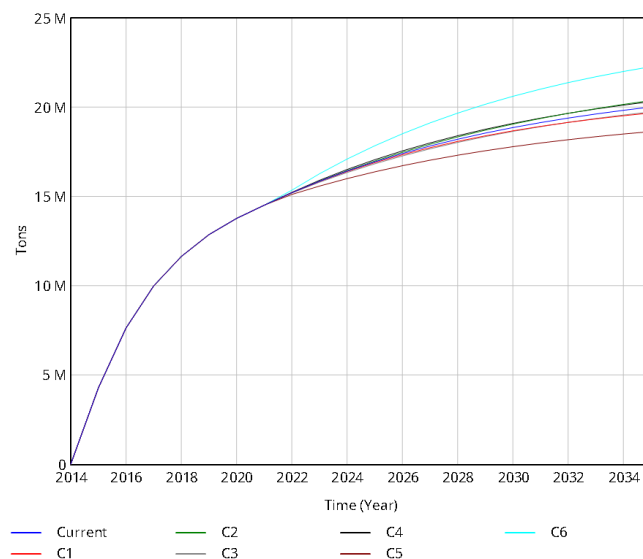


Figure 11 Cumulative total pollutant emissions in manufacturing under different scenarios

According to the simulation results, Scenario C5 performs the best in terms of reducing pollutant emissions, followed by Scenario C1. The digitalization driven by the digital economy allows for more accurate monitoring of pollutants, which leads to greener production practices. However, digitalization alone does not directly reduce pollution.

In contrast, Scenario C5 adjusts the proportion of green patents, which directly reduces pollutant emissions during the production process, resulting in a stronger overall impact. Specifically, Scenario C1 and Scenario C5 reduce cumulative emissions from 2022 to 2035 by 2% and 7%, respectively, compared to the current scenario.

Additionally, when adjusting the research factor, we observe that while increasing research level typically leads to a larger production scale—and thus higher pollution emissions—this also enhances the output of green technologies, which helps control pollution. In general, higher levels of scientific research will lead to lower pollution emissions.

## 5. Conclusions and Recommendations

The integration with the digital economy is transforming the manufacturing sector. As environmental issues receive increasing attention, how the digital economy will impact the green transformation of manufacturing to achieve environmental protection has become an important topic. This paper adopts a system dynamics perspective to explore these issues. It constructs a SD model to analyze the dynamic impact of the digital economy on the manufacturing industry and explore how it may evolve. The study concludes with a series of conclusions and recommendations to promote the green transformation of the industry.

### 5.1 Conclusions

In terms of the manufacturing sector's value-added growth, accelerating the development of the digital economy can significantly increase its value-added contribution and drive high-quality development. While increasing investment in research and development (R&D) can also boost manufacturing value added, the impact is comparatively smaller.

Regarding energy consumption, increasing the adoption of green technologies can quickly reduce energy usage, carbon emissions, and water consumption. These measures are particularly effective in the short term and are well-suited for industry-specific green transitions to address immediate environmental challenges. In a scenario where the digital economy develops at a faster rate, the manufacturing sector also demonstrates excellent performance in energy efficiency and emission reduction in the long term, and there is a cumulative effect of this process, with energy efficiency and emission reduction being strengthened over time, so that its role is more pronounced in the long term.

On the issue of pollution emissions, green technologies have the most significant impact by reducing pollution during the production process. In comparison, the digital economy has a more limited direct effect on reducing pollution emissions, though it plays a supporting role in overall sustainability efforts.

### 5.2 Policy Recommendations

Enhance the digitalization of the manufacturing sector by promoting the adoption of advanced digital tools and platforms. This will improve resource management, optimize efficiency, reduce energy and water consumption, and lower carbon emissions, supporting both sustainable economic growth and environmental protection.

Leverage digital technologies to implement advanced monitoring systems that track emissions, energy usage, and water consumption in real time. This data can inform policy adjustments and help ensure that manufacturing aligns with environmental and climate goals. Enhanced monitoring will also facilitate the enforcement of climate regulations and accelerate the transition to sustainable manufacturing practices.

Increase research funding for the development of green technologies that reduce carbon emissions, energy consumption, and water usage. Provide incentives for manufacturers to adopt green technologies, such as tax breaks, subsidies, and grants for green patent development.

Design and enforce policies that promote sustainable practices in manufacturing, with a focus on reducing energy consumption, minimizing carbon emissions, and conserving water resources. Such policies should integrate digital and green technologies, achieve a balance between economic efficiency and sustainable development.

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